UNSEEN MASS

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INTRODUCTION

The arguments for "unseen mass", and the evidence on its distribution, are still somewhat controversial as far as the details are concerned. The following four statements would, however, be widely accepted:

(i) Baryons cannot contribute much less than 1% of the critical density - i.e. $\Omega_{baryon} \gtrsim 0.01$. This limit comes from the "luminous" content of galaxies, and from the inferred amount of X-ray emitting gas in clusters.

(ii) $(M/L)_B$ values in the range around 200 h_{100} are derived from studies of virialised clusters and from the cosmic virial theorem. These refer to length scales of $(1 - 2)h^{-1}_{100}$ Mpc.

(iii) $(M/L)_B$ appears to be a non-decreasing function of length scale.

(iv) If $\Omega \simeq 1$ — the value favoured by some theorists, especially the advocates of "inflationary" cosmology — then $(M/L)_B$ must continue to increase out to at least $\sim 10\ h^{-1}_{100}$ Mpc. Otherwise, a high density Universe would be incompatible with the low random velocities which lead to conclusion (ii) above.

The straightforward relationship

$$\langle M/L \rangle_B \simeq 2300\ (\Omega h_{100}) \qquad (1)$$

shows that 90% (or even, if $\Omega \simeq 1$, as much as 99%) of the mass-energy in the Universe must be in some form with much greater M/L than the objects that astronomers normally investigate.

G. O. Abell and G. Chincarini (eds.), Early Evolution of the Universe and Its Present Structure, 299–305.
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https://doi.org/10.1017/S0074180900039218 Published online by Cambridge University Press

2. CANDIDATES FOR "UNSEEN MASS"

Neutrinos or Other "...inos"

If neutrinos have non-zero masses, then

$$\Omega_\nu = 0.03\, h_{100}^{-2} \left(\frac{n_\nu}{n_\gamma} \right) \sum_{\text{species}} (m_\nu)_{ev} \quad ,$$

where n_γ is the photon number density in the microwave background (and two-component neutrinos are assumed). In the "standard" hot big bang theory, $n_\nu/n_\gamma = 3/11$ (provided that the rest masses are not so large that mc^2 is comparable with kT at the temperature ($\sim$ 1 Mev) when neutrinos decouple); so one species with mass 100 h_{100}^2 suffices to give $\Omega_\nu = 1$.

Theoretical physicists have other particles in reserve - photinos or gravitinos, for instance - which could (if they existed) contribute to Ω in an analogous way. The only difference would be that (n/n_γ) could be less than for neutrinos because the other "...inos" may have decoupled before muons (or even hadron pairs) annihilated - the latter would then boost the neutrinos but not the still more weakly coupled "...inos". For gravitinos, we may have $(n/n_\gamma) \lesssim 10^{-2}$. Szalay will discuss this topic in more detail, so I will make just two remarks about neutrinos, etc.:

(a) If neutrinos dominate the dynamics of galaxy formation, then there is a characteristic mass-scale of $\sim 2 \times 10^{18} (m_\nu)_{ev}^{-2}\ M_\odot$, which is of "supercluster" size for $m_\nu \simeq 10$ ev. (This is the horizon mass at the stage when $kT = m\,c^2$, and can also be expressed as $m \sim m_{Planck} (m_\nu/m_{Planck})^{-2}$.) For other "...inos" this mass may be of galactic order.

(b) Considerations of primordial nucleosynthesis yield a well-known general argument favouring <u>non</u>-baryonic "unseen mass". The observed deuterium abundance cannot be produced in the big bang unless $\Omega_b < 0.015\, h_{100}^{-2}$. A baryon density within a factor of two of this limit fits best with the data on other light elements (^{3}He, ^{4}He, ^{7}Li). Advocates of a high Ω_b must appeal to an "astrophysical" origin for D, or else to the "escape clauses" permitted in non-standard big bang models (e.g. David and Reeves 1979).

Baryonic "Unseen Mass"

If galaxies and clusters evolved hierarchically from sub-units that condensed earlier, most of the initial baryons might have been incorporated in a pregalactic Population III. Ideally, one would like to be able to calculate what happens when a cloud of $10^6 - 10^8\ M_\odot$ condenses out soon after recombination - does it form one (or a few) supermassive objects, or does fragmentation proceed efficiently down to low-mass stars? Our poor understanding of the initial mass function (IMF)

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for stars forming now in our own Galaxy gives us little confidence that we can predict the nature of pregalactic stars, forming in an environment differing from our (present-day) Galaxy in at least four significant ways:

(i) The initial cloud masses may be larger than any dense clouds in our Galaxy - the maximum scale on which $\delta\rho/\rho \simeq 1$ at recombination depends on the initial fluctuation spectrum, but may be as high as 10^8 $M_\odot$.

(ii) There may be no coolants apart from H and He.

(iii) The microwave background prevents cooling below $\sim 3(1+z)^\circ K$.

(iv) The energy density in background radiation ($\propto(1+z)^4$) is so high that "Compton drag" may inhibit free-fall collapse if the material is partially ionized.

Kashlinsky and I have (1982) tried to investigate these processes in some detail, but we reach the depressing conclusion that one cannot yet confidently pin down the masses within even ten orders of magnitude (10^{-2} - 10^8 $M_\odot$)! Starting with a post-recombination bound cloud of 10^6 - 10^8 $M_\odot$, there are two extreme possibilities. Fragmentation may be so ineffectual that a single supermassive object results. On the other hand, if fragmentation were maximally efficient, we could end up with 10^{-2} $M_\odot$ stars, this being the Jeans mass if the material compressed to the highest density ($\sim 10^{10}$ cm^{-3}) permitted by the clouds' likely initial rotation, and turned into H_2 at $\sim 10^3$ °K.

Astrophysical and Observational Constraints on the Masses of Population III Remnants.

Despite our inability to "predict" what Population III should be like, there are several constraints which together allow us to conclude that the masses must either be $\lesssim 0.1$ $M_\odot$ or else in the range 10^4 - 10^6 $M_\odot$.

The (M/L) ratio. Relation (1) obviously rules out masses above 0.1 $M_\odot$ unless the stars have all evolved and died, leaving dark remnants.

Nucleosynthesis, background light etc. A severe constraint comes from the requirement that Population III should not overproduce heavy elements. If this population predates all Population II, the fraction of heavy elements produced must be $\lesssim 10^{-4}$; if Population II and Population III are coeval, maybe up to 10^{-3} is permissible. This sets strict limits on the mass fraction going into the upper mass range for "ordinary" stars (15 - 100 $M_\odot$). Limits on the range 100 - 400 $M_\odot$ are uncertain because only ^{4}He may be ejected, the "heavies" in the core collapsing into a black hole remnant. An uncertainty in the evolution of massive or supermassive stars is the amount of mass loss during H-burning; however an IMF such that most mass goes into very massive objects (VMOs) of $\gtrsim 10^4$ $M_\odot$ is compatible with the nucleosynthesis constraints. A further consideration favouring these high masses is that they are likely to terminate their evolution by a collapse which swallows most of the mass - if most of the

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material were ejected we would need to invoke "recycling" through several generations in order to end up with most of the material in black holes rather than gas.

The background light constraint depends on the redshift at which the VMOs form, and on whether the energy can be thermalised (see Rowan-Robinson's contribution to these proceedings).

Detailed discussions of Population III are given by Carr, Bond and Arnett (1982) and by Tarbet and Rowan-Robinson (1982).

Dynamical friction, etc. Carr (1978) has reviewed the effects of massive black holes on the dynamics of our galactic disc and the effects of accretion, showing that our Galactic halo cannot be composed of objects whose individual masses exceed $\sim 10^6$ $M_\odot$. This limit cannot however be applied to the more diffusely-distributed objects that might contribute $\Omega \simeq 1$.

Gravitational Lenses

If a remote source (e.g. a quasar) is sufficiently compact, the probability that our line of sight passes close enough to one of the Population III objects for significant lensing to occur is $\sim \Omega$. Note that the individual lensing masses do not affect this probability, only their total contribution to Ω. The characteristic scale of the images is

$$\theta \simeq 10^{-6} \left(\frac{M_{\rm lens}}{M_\odot} \right)^{\frac{1}{2}} \text{ arc sec.} \qquad (2)$$

The precise coefficient in (2) is, of course, a function of the source and lens redshift and of the cosmological model, but is ~ 1 for sources with $z \gtrsim 1$ and lenses $\sim \frac{1}{2}$ way along the line of sight.

The structure on milli-arc second scales predicted by (2) for 10^6 $M_\odot$ holes could be detected by VLBI. For "Jupiters" of $\lesssim 0.1$ $M_\odot$ there is no short-term hope of achieving the angular resolution required ($< 10^{-6}$ arc seconds); however there is then a chance of detecting variability on timescales of years due to transverse motions of the sources themselves (Gott 1981, Young 1981). Such variability would be found only in source components whose intrinsic angular size was less than the θ given by (2). For $z \simeq 1$ this requires linear dimensions of around a light day or less. The region emitting the quasar optical and X-ray continuum probably fulfils this requirement, but its rapid intrinsic variability would be hard to disentangle from effects due to lensing. Canizares (1982) argues that one can already exclude $\Omega \gtrsim 1$ in "Jupiters" because the apparent magnitude of the typical quasar continuum region would then be altered by a factor ~ 2 relative to that of the (larger) line-emitting component, thereby introducing an unacceptably large scatter in the equivalent widths of quasar emission lines. (For a related argument, see Setti and Zamorani's contribution to these proceedings.)

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3. LARGE-SCALE SEGREGATION OF LUMINOUS AND "UNSEEN" MATERIAL

We only observe the 1 - 10% mass fraction of the Universe that is in "luminous" galaxies. To what extent is this a valid tracer of the total mass distribution on various scales? The answer to this question, for scales (2 - 100)h_{100}^{-1} Mpc, is relevant to three key issues: (i) Is $\Omega \simeq 1$ possible? (ii) What is the nature of the "voids"? (iii) Can the observed clustering of galaxies be the outcome of purely gravitational forces?

One cannot yet give confident answers to any of these questions. Szalay's paper discusses galaxy formation in neutrino-dominated cosmology, where dissipation can separate baryons and "unseen" neutrinos on scales at least up to the characteristic damping mass; on the other hand, for an initial fluctuation spectrum with a high wave number cut-off, purely gravitational effects can perhaps adequately reproduce the "linear" features of the observed galaxy clustering (Klypin and Shandarin 1982, Davis, Frenk and White 1982). The figure shows schematically how the "mass fraction" of the Universe may be apportioned between "unseen mass" gas and galaxies. Gas ↔ galaxy processes continue up until recent epochs; moreover, the differing effects of dissipation, dynamical friction, etc. on the three components will cause their ratio to vary spatially.

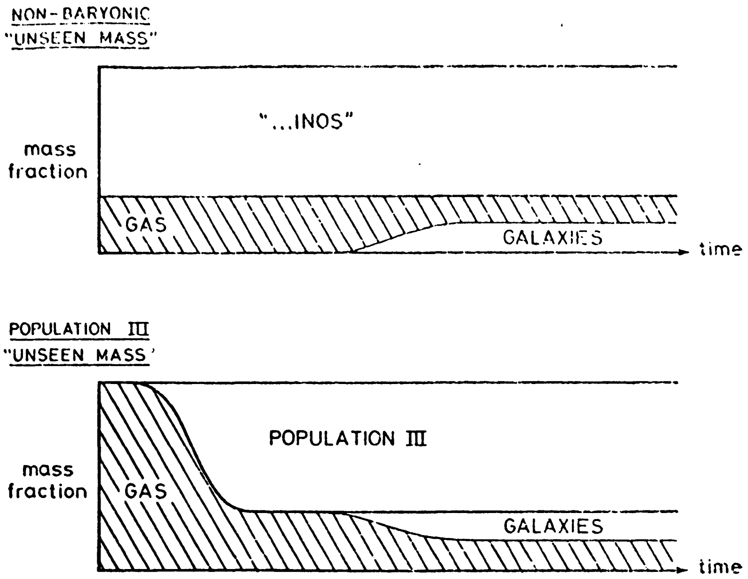

Figure 1. Cosmic 'mass fractions' as a function of time.

I should like to draw attention to two ways in which galaxy formation may be inhibited in large volumes, without the baryon content of those volumes being depleted.

(a) Heating of pregalactic gas to $\sim 10^6$ °K would make M_{Jeans} higher than a galactic mass, and inhibit condensation of protogalaxies.

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This would require pregalactic energy input as envisaged in the Ostriker-Cowie (1981) scheme. However, it is much less extravagant in terms of energy to heat up a large volume than to evacuate it: 10^6 °K corresponds to only ∼ 100 ev per proton, whereas to evacuate a "void" as large as that discovered by Kirshner *et al.* (1981, and these proceedings) would require ∼ 10^5 ev per proton.

(b) Several models for the evolution of primordial density fluctuations lead to a post-recombination spectrum of slope $n \simeq -3$ on mass-scales up to superclusters. This spectrum has the property that $\langle(\delta\rho/\rho)^2\rangle$ is independent of scale – it is not the case that smaller scales have larger amplitude and condense out at earlier epochs. The important consequence ensues that few galactic-mass perturbations in incipient voids would be gravitationally bound, and even purely gravitational effects would inhibit galaxy formation in regions destined to lie outside clusters.

Either of the above schemes (or some combination of the two, whereby galaxies form first (for reason (b)) in incipient superclusters, and their power output heats the intervening volume) would give rise to voids which could contain *more* gas than apparent clusters, and where even the baryonic component could be much more homogeneous than the distribution of galaxies might indicate.

4. CONCLUSIONS

The acceptable forms for "unseen" mass can be listed as follows:

Non-baryonic	∼ 10 ev neutrinos	(10^{-32} gm)
	Other elementary particles (photinos, gravitinos, etc.)	
Baryonic	"Jupiters" of < 0.1 $M_\odot$	
	10^4 - 10^6 $M_\odot$ black holes	(∼ 10^{37} - 10^{39} gm)
	Diffuse gas in "voids"	

Observations may soon reduce the range of options. Alternatively, they may show that more than one type of unseen mass exists: there may, for instance, be a widely-diffused non-baryonic component, as well as a large number of Population III remnants concentrated in the halos of individual galaxies. But at the moment our ignorance is encapsulated by the statement that there are still > 70 powers of ten uncertainty in the masses of the entities that constitute > 90% of the content of the Universe!

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Discussion

Salpeter: The formation of low-mass stars out of pure H and He may select against high-velocity turbulence (which can dissociate H_2, which in turn prevents radiative cooling) and for high gas density. These "Jupiters" might then be concentrated to the innermost cores of rich clusters.

Rees: In the scheme Kashlinsky and I have discussed, the best chance of obtaining dense H_2 would occur if a rotationally-supported disk can form (maybe around a central massive object). There are, however, some effects which would make it easier for H_2 to form (or to re-form after shock heating) at early epochs. At, say, $z \simeq 300$, the radiation temperature is $\sim 10^3$ K. Moreover, its energy density is high enough that an electron can Compton-cool to the radiation temperature before recombining. A high density of free electrons or negative ions at a low temperature provides very propitious conditions for molecule formation.

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